Chapter

Degradation and Improvement of Urban River Water Quality

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Abstract

The need to understand urban water quality has become a very important area of research and management in the aquatic sciences. Decades of urban development generating high rates of impervious surface, complex networks of stormwater control mechanisms and declining river water quality has created a demand for greater study. In this chapter, issues such as stream bank erosion, flooding, sediment pollution, bacteria and channelization are presented as drivers of the urban water environment. Methodologies and study designs to document these impacts are discussed. Ideas to improve the urban condition such as retrofitting previous development, infiltration of surface runoff, stream restoration, dredging and rehabilitation of lakes and compartmentalization of future development are explained and detailed as ways of integrating the natural landscape features into improvement of our urban centers. Finally, the incorporation of citizen science into adaptive policy is suggested as a solution to regulatory and esthetic/recreational need for improvement.

Keywords: Urbanization, Water Quality, Stormwater, Best Management Practices, Sediment Pollution

1. Introduction - how did we get here?

Urban environments including our buildings, roads, traffic, residences, industries, sewage treatment systems, population centers, parks and precipitation patterns all intertwine creating observed water quality in these communities. Water resources and the people living in and around them are intricately linked whether we understand this or not. The observed impact is now so pervasive scientists have suggested a new epoch beginning in the 1950s as the Anthropocene. Regardless of the label, this current age of human influence on the environment is very pervasive creating many stressors that plague water quality. Excessive sediment and erosion mixed with microplastics, pathogens, toxics and nutrients flow through our urban rivers daily. In order to improve this condition, we must first understand the origins.

Our rivers were not always degraded. Nature exists in a state of dynamic equilibrium with our surroundings. Rivers are no different. The river is in equilibrium with its drainage area. Historically, precipitation struck vegetation directly infiltrating into the ground as it was not covered by development. Entire watersheds were vegetated and these are the conditions rivers and streams equilibrated into. Precipitation flowed into the river but mainly through the surrounding soil first. The watershed stored precipitation in the ground, purified it as it slowly migrated toward the stream then released it through lateral discharge into our rivers. Any precipitation flowing over land only occurred during large storms and this input was periodic. Thus, the size and shape of streams and rivers reflected this pattern. The river system sometimes flooded but not as a catastrophic event. It flowed into the floodplain adjacent to its banks where essential nutrients and replenishing sediments sustained the river system. Rivers created a mosaic of serpentine meanders from mountain headwaters to the coast gently changing while moving sediment from one bank to another. It was a river in harmony with its surroundings.

But floodplains are flat and the alluvial soil desirable. Building projects need flat land for development and farmers need good soil for crops. These floodplains became premium resources early in our history before we learned to flatten plots of land for our buildings and fertilize soil for our crops. We developed floodplains around major rivers that soon became urban centers. Development moved up the water course fanning throughout the drainage basin. Rivers were our first highways, so commerce easily moved along these waterways and development prospered at major ports.

Precipitation contacting these built impervious surfaces instantaneously generated a new pattern of water flow. Water that previously traveled through groundwater now flowed as surface runoff. A river once in harmony with its surroundings and dependent on groundwater (a term called hyporheic flow) now became a conveyance for surface water discharge. In response, the river eroded to gain harmony with this *new* pattern of flow. Development increased, engineers designed more conveyances, pipes, levees and floodplain relevation to alleviate flooding and remove water quickly from our built surfaces. Now contaminated and not purified, surface water became the predominate input into our rivers. More built environments created ever increasing discharge resulting in dangerous flooding. To contain this problem, retaining walls were built. River erosion multiplied as construction continued throughout the watershed. As this intensified, encasement of the river into pipes and culverts became the standard of management. What was once a majestic river flowing through a beautiful landscape naturally purifying itself was transformed into an artificial conveyance filled with polluted water.

1.1 The paradox of development

Our social evolution further exacerbated this problem. The built environment is expensive and with the advent of indoor plumbing an extensive system of water movement became necessary. These pipelines were built under the construction then along the river banks impacting its natural flow. Large scale purification plants appeared at the river mouths. The extensive urban network required rapid and efficient movement of water away from surfaces so extensive systems of stormwater drainage began to appear. Environmental regulation multiplied requiring more and more infrastructure with development. The landscape became an intricate stormwater and sewage drainage network littered with culverts, sedimentation ponds, curb and gutter and isolated streams only noticeable over bridge crossings.

To pay for this, urban governments taxed the land that was developed. Zoning of land became commonplace and classification as improved or unimproved was designated. Governments believed building upon the land improved it because such lands generated greater tax revenue. But from an environmental perspective, these projects were not improvements but environmentally liabilities increasing in cost over time.

Thus the paradox. Often, urban governments have autonomy over local land decisions. As a result, property is taxed and local governments funded. Government revenue increases with land improvements creating the need to grow in order to meet increasing population demands. Local governments find the need to approve

Figure 1.
A river flowing through the urban landscape.

development to support its infrastructure and the cycle continues. It is difficult to suggest stopping this because you are asking government to stop funding the essential services you need such as police, fire protection, schools and roads.

As this development continued, groups of environmental researchers began to observe how rivers were responding. Leopold et al. [1] called it the urbanization cycle where heavy development caused rapid sedimentation followed by fundamental changes in river hydrology. In the same year, Walsh et al. [2] along with Meyer et al. [3] coined the term urban stream syndrome. The descriptions were alarming. With development, the stream channel begins to deepen and widen with the banks becoming unstable and eroding. Deepening of the river isolates it from the floodplain resembling a simple conveyance rather than an integrated stream course. Continued overdevelopment isolates remaining ecological services provided by trees, soil and wildlife. As waste and energy needs for the urban system intensifies, the cycle of erosion and isolation continues (**Figure 1**).

2. Urban river degradation

Full urban development then creates a disconnect between the benefits of urban infrastructure and the environmental costs needed to sustain it. A state of evolving equilibrium or permanent disequilibrium occurs generating pressing problems that become difficult to solve. These problems are becoming well studied and documented.

2.1 Erosion and sediment mobilization

Erosion is the fastest and most prominent visual effect of urbanization. Wolman [4] is credited with some of the earliest documentation of erosion and sedimentation directly attributed to the built environment. His observations documented export of sediment from forested watersheds (< 40 tons/year/Km^2) into agricultural (120-320 tons/year/Km^2) to urbanized/developed (>4,000 tons/year/Km^2). Further research into this problem yielded estimates from active construction as high as 50,000 tons/year/Km^2 [5]. The impact is diluted depending on the size of the watershed but nonetheless problematic. The final observation by Wolman [4] visually described his observations. Our urban river environment is a panorama of flood debris, sand, scoured bottoms and exposed sediment. Unfortunately, this still accurately describes the condition of many urban rivers today.

Further research and understanding of this paradigm were advanced by Chin [6]. She quantified that initial urban development mobilizes sediment on the magnitude of 2-10 times the natural rates. After development subsides, lower sediment yields predominate (< 30 tons/year/Km^2) but a new hydrology is established. A new and enlarged river channel 2 – 15 times the original size is needed to accommodate changing water volumes discharged directly to the stream. Even though the stream enlarged, erosion continued at a rate of about 0.3 meters per year [6]. Erosion will continue until the stream channel equilibrates to watershed disturbance or more likely never subsides due to a constant pattern of disequilibrium. Discolored urban rivers of brown or orange are typical during most rain events because of this problem.

Current analysis by Gregory [7] and Maklin and Lewin [8] suggest a more holistic paradigm for river change. Time has elapsed since early urbanization impacted river systems and researchers now incorporate time scales into thinking about human impact on these systems. Small scales and short time periods cannot encompass the entirety of impacts. River systems are variable and differential in response to perturbations. While some systems are resilient others are not. Some move into a sustainable pattern while other continue a disequilibrium continuously. All river systems are impacted and now researchers are working to quantify this impact.

Because precipitation is such a strong driver on these systems, as long as the natural pattern of infiltration has been disrupted we will continue to have problems. Some river systems are continually plagued by a dense blanket of eroded material while others suffer from highly erodible river banks. These problems began in the climatically benign twentieth century [8] but will need solved under changing climatic conditions and new precipitation patterns of the next century. This may prove more challenging or even catastrophic than anything we have previously faced. Rivers need to be understood from a global scale to within small reaches to encompass the entirety of change.

2.2 Changes in morphology and channelization

Beyond erosion, the continuing negative impact of a new hydrology on the physical (morphology) of the river environment is quite destructive. Excessive flow is disruptive and causes scouring of the stream bed, loss of habitat, streambank incision and isolation of the floodplain from the main channel [9]. High flow increases sheer stress on river bottom material scouring and pushing it downstream in what is called bedload. This scouring removes gravel and other material in the range of 2-64 mm [10] replacing it with bars and benches from material washed from erosional sediment above [6]. During dry periods, lack of infiltrating precipitation lowering the water table reduces lateral discharge. This creates periods of low flow degrading the aquatic environment further [11]. Rivers become 'flashy' suggesting periods of very high and very low flow rather than a consistent and stable hydrological regime.

Macroinvertebrate and fish habitat suffers. The good quality sediment and riffle habitat that the 2-64 mm material created is lost eliminating the essential refuges for aquatic life. Replacement sediment bars and benches subject to similar bed sheer stress [12] constantly change making this new environment unstable. Continual stream bank erosion adds more sediment to the stream channel until isolation from terrestrial interaction is completed [13]. Food webs become disconnected as we see less biodiversity and abundances of fish, aquatic life and the woody debris these problems generate [14].

Isolation from the floodplain is very problematic. Restriction of this hyporheic exchange limits nutrient reduction, temperature regulation and pollutant removal [15]. Rivers are part of a larger and interconnected system that cannot function well in isolation. Without the purifying mechanisms and ecological connectivity of the floodplain, the river is reduced to nothing more than a water conveyance.

2.3 Pollution problems compounded by sedimentation

Sediment mobilization from changing hydrology further complicates the pollution problems surrounding urban environments. Sediment is known to transport increased levels of many pollutants [16]. Influxes of plastics, debris and other solid waste flow freely into rivers because of direct stormwater and overland flow. Land in proximity to urban areas and watersheds with a high urban land use strongly correlate with increased concentrations of microplastics [17, 18]. Microplastics once mobilized into the river environment are concerning because of their ability to sorb/release persistent organic contaminants [19, 20]. These plastics also act to transport and provide surfaces for the growth of microbiological pathogens [21]. This complicates efforts to reduce the bacterial loading we find in these systems and heightens the concern for disease. Finally, the transport of these microplastics into the oceans from urban river drainage is very concerning and problematic [19, 22]. This problem must be controlled first in urban watersheds to provide any hope of reducing the impact in our oceans.

Pathogens (bacteria, protozoans, viruses) easily flow through the urban river environment entering from stormwater, wastewater and overflowing or leaks from sanitary sewer systems. Of these sources, stormwater generates the greatest impairment to urban rivers because of water volume [23] and concurrently is the greatest concern for disease outbreak. Using climate and epidemiological records, Rose et al. [24] found statistical evidence suggesting a correlation between storm events and disease outbreak in cities. Sediment loading of river beds along with organic material provides a good environment for bacteria such as *E. coli* to survive until the next storm event re-suspends them into river water. Pachepsky and Shelton [25] found the survivorship of *E. coli* in sediments was much greater than in overlying waters. Mallin et al. [26] attributed continual bacterial contamination from a sewage spill to release from underlying sediments well after levels depleted in overlying water. This creates the concern that urban rivers harbor extensive beds of bacteria, potential pathogens and other pollutants that will be resuspended continually as sediment and plastics move through these systems.

2.4 Flooding and impervious surfaces

Interwoven into all of these problems are the changes in flood periodicity and intensity. The urban drainage network influences the river flood regime from response time due to precipitation events through the ultimate magnitude of the flood [27]. The highly impervious urban watershed has a diminutive ability to minimize flooding generating ever increasing amounts of surface runoff [28].

Development acts to amplify the runoff response causing smaller and smaller precipitation events to generate larger and larger flood events. Rainfall intensity rather than duration then becomes the driving force behind urban flooding.

Researchers investigating this phenomenon began to characterize these patterns and search for solutions. Initial characterization suggested nonporous landscapes like parking lots and buildings behaved collectively as an impervious barrier to precipitation infiltration. Calculated as a percentage, increasing coverage corresponded directly with greater volume of stormwater discharge into a river without treatment. Researchers studied how these impervious surfaces operated then incorporated these ideas into a model of impervious cover [29]. The model suggests an increasing level of stream degradation corresponding to incremental thresholds of impervious surface. Increases up to 10% of impervious surface throughout a watershed cause the river to become sensitive to inputs. Between 10% and 25%, the river becomes impacted or impaired. Beyond 25% impervious cover, the river becomes non supporting of essential river functions.

Further research found that stormwater infrastructure is actually more predictive of stream degradation than percentages of impervious surfaces [30, 31]. Research suggests that the increased complexity of stormwater of pipes and drains, the greater the impact on receiving streams. Effective Impervious Surface (EIA) was developed as a better descriptor than Total Impervious Surface (TIA) when predicting river response [32]. EIA uses the connectivity of stormwater discharge directly into the river where TIA calculates only the total surface area. Schuster et al. [28] explains the problems associated with EIA. With just a 10% level of effective impervious surface (EIA), runoff production increases to the extent that 2-year intensity storm now yields the same amount of discharge to the river as a 10-year storm. This is profound because stormwater infrastructure has now fundamentally changed watershed function. Smith et al. [27] found that the five largest floods in past 74 years in Charlotte, North Carolina occurred after 1995 suggesting that the drainage density (EIA) created this response. Such conclusions are corroborated throughout the literature [33] generating concerns that urban watersheds fundamentally changed by EIA are ill equipped to protect streams and rivers from impending climate change.

2.5 Stormwater infrastructure

Most stormwater infrastructure was built around the central premise of peak attenuation. Development requires mitigation of excessive stormwater created by the impervious surface. Most often this is some form of detention pond or other structure to slow water flow into a receiving river. The theory behind these structures is to capture the newly created runoff from development, hold it in place and then later release it at rates no greater than the pre-development peak. Thus, the peak is shaved and flattened and theoretically mimics what was discharged before development. Ecologically, this theory is flawed because a new and different stormwater peak has been generated. Roesner et al. [34] reviewed why this is so damaging to the river environment. This practice exposes the stream to extended periods of flow rather than the previous slow infiltration and discharge vegetated watersheds provided. While the peak is shaved, a greater volume of surface runoff is created and receiving streams are not in equilibrium to receive it. Further, the one size fits all mentality of design ignores unique attributes of urban landscapes for expediency. Meeting only minimum regulatory requirements (usually no greater than a ten-year storm) has built a watershed landscape that is easily overwhelmed during high intensity precipitation. Intensity-duration-frequency (IDF) curves used to engineer stormwater infrastructure may have undersized the entirety of our urban landscape as climate change impacts future precipitation patterns [35].

Even more problematic, these structures condense what was once a diffuse overlay of precipitation throughout an area into a single point discharge. This has immense ramifications on the receiving stream channel. While these structures are capable of storage and attenuation of small storms, research suggests they are highly ineffective for larger storms [36]. Further, these structures are not protective of overall degradation and any protective capabilities reduce with age [37]. Stormwater infrastructure will be very problematic as we desire to improve watersheds in the future.

3. Monitoring water quality in urban Rivers

Good quantification of urban impacts on rivers is needed to determine levels of degradation and begin the rehabilitation process. Depending on instrumentation, budgets and personnel; many water quality parameters are available with various uses toward the prediction of water quality (**Table 1**). Decisions on what to measure rests behind the objectives of the study and translation into effective policy for improvement.

Decision making begins with methodology and site selection gaining good access to a river for study. Barbour et al. [38] outlines several approaches. A targeted study where concerns over a specific outfall or disturbance entering the river may be one approach. Here, samples are taken above, in and below the concern. Comparisons are made to determine the extent of impact. Another approach is collection of information to assess the overall condition of the river and watershed. Sites are selected throughout the river basin then compared to a reference condition or norms of water health. In severely degraded urban areas historical data may be necessary for comparisons.

Concerning seasonality, samples should be taken during each significant season then characterized. Based on findings, an index time period is created to meet objectives. This allows the investigator to collect data during that time period and interpret findings within the bounds of the study. This approach is good for an overall analysis of urban river quality. If specific outfalls or problem areas are the concern seasonality may not need analysis.

Methodologies are dependent upon the parameter used. Water samples are measured using field instrumentation such as submersible meters and laboratory analysis detailed in publications such as Standard Methods [39]. Insects are collected using various types of nets, preserved and later sorted then enumerated. A rapid bioassessment (RBA) technique developed by Barbour et al. [38] is possible or if a more detailed approach is needed the use of bottom samplers such as a Surber or Hess is warranted. Comparisons between RBA and Surber methods have been studied [40]. For fish collections, electrofishing is the preferred collection technique [41]. It describes the pulsing of DC current into water temporarily immobilizing fish allowing collection for analysis.

Chemical water quality parameters are used individually or compiled into a metric dependent upon the investigator and the study. More data strengthens conclusions, however any data collection derived through a targeted study is beneficial. In 1970, a group of 142 water quality scientists developed a Water Quality Index (WQI) [42]. Using 9 prominent parameters (dissolved oxygen, fecal coliform/*E. coli*, pH, biochemical oxygen demand (BOD) (5-day), temperature change (from 1 mile upstream), total phosphate, nitrate, turbidity and total solids) the index was created for use in defining water quality. Multiple variations of the WQI have evolved (reviewed by Bharti and Katyal [43]) and are effective within defined use. Further, Noori et al. [44] explored the substitution of alternative measures into the

Parameter	Description	Uses
Dissolved Oxygen	Concentration of oxygen dissolved in water.	Loss of oxygen suggests organic pollution and high BOD. Supersaturation suggests nutrient pollution and stimulation of plant growth.
Temperature	Heating and cooling of the water.	Urbanization creates heat islands warming river water.
pH	Changes in the hydrogen ion concentrations.	Rising pH suggests loss of organic material entering stream from deforestation. Runoff from impervious surfaces increases pH.
Conductivity	Measure of strength of electrical charge.	Direct correlation between increasing conductivity and pollutants. Sewage contains a very high conductivity.
Alkalinity	Buffering capacity.	Poorly buffered rivers have significant changes in pH.
ORP	Oxidations and Reduction Potential.	Healthy streams are well oxidized and pollution tends to drive ORP lower.
Turbidity	Discoloration of water.	Water increases in turbidity as it is polluted with sediment and other pollutants.
TS, TSS and TDS	Measure of solids in water.	Suspended solids are a form of pollution increasing as water degrades. Important to distinguish between Total Solids (TS), Total Suspended Solids (TSS) and Total Dissolved Solids (TDS) when making conclusions.
BOD	Biological Oxygen Demand.	Oxygen consumption by bacteria breaking down organic matter. Increases in BOD degrade water quality.
Fecal Coliforms/*E. coli*	Bacterial contamination and pathogen estimation.	Indicators of disease potential and increases suggest water of worsening quality. At certain levels of contamination water should be avoided.
Phosphorus	Concentration of limiting nutrient.	Believed to be a keystone pollutant due to very low concentrations in freshwater suggesting increases in this nutrient signal increases in many pollutants.
Nitrogen	Concentration of polluting nutrient.	Various species of nitrogen helpful in pinpointing types of pollution such as agricultural runoff or sewage contamination.
WQIs	Various indices predicting water quality using chemical parameters.	Compilation of many combinations of chemical measures to produce an overall measure of water quality. May be limited to short-term changes in river quality.

Parameter	Description	Uses
IBIs - Macros	Various indices predicting water quality using aquatic insect abundances and diversity.	Compilation of many combinations of macroinvertebrate assemblages (abundance, diversity and sensitivity) to produce an overall measure of water quality. Better measure as these insects integrate environmental change over longer time periods.
IBIs - Fish	Various indices predicting water quality using fish abundances and diversity.	Compilation of many combinations of fish assemblages (abundance, diversity and sensitivity) to produce an overall measure of water quality. Good measure as fish integrate environmental change but mobility and habitat destruction must be considered.
Remote Sensing	Estimates of water clarity, chlorophyll concentration, organic and mineral suspended material.	This technique uses the visible and near infrared light bands of the solar spectrum to predict water quality through correlations between the water column reflections and known concentrations of parameters measured. This technique is not adequate alone but very useful in coordination with other measured parameters.
Data Loggers	Dissolved Oxygen, Conductivity, Water Level and pH.	Data loggers allow deployment into water environments to capture continuous data for a particular parameter. These loggers are highly advantageous for long term data acquisition and areas hard to access. They need to be well moored to structures to avoid loss during extreme flooding events.
Water Quality Models	Most common include: AQUATOX, CE-QUAL-W2, Environmental Fluid Dynamics Code (EFDC), QUALs (QUAL2E, QUAL2E-UNCAS, QUAL2K, and QUAL2Kw), Soil and Water Assessment Tool (SWAT), Spatially Referenced Regression on Watershed Attributes (SPARROW), and Water Quality Analysis Simulation Program (WASP).	Models are used to assist in effective water quality management and to assist in decision making. Models are also useful in reducing the need for extensive sampling. It is important to note the region, precision and ecosystem specifics for each chosen model. Models are a good choice to assist with management decisions.

Table 1.
Water quality measures along with descriptions and uses.

original WQI. Changes in water quality classification were observed when other parameters are substituted so care must be exercised when calculating the WQI.

Overall, WQI is a good predictor of water quality and useful in river characterization. However, the ability to monitor all required parameters may be beyond the capabilities and means of a researcher. Kannel et al. [45] suggested a minimized WQI version using only 5 parameters (Temperature, pH, Dissolved Oxygen, Conductivity and TSS) and an additional index using only dissolved oxygen as an effective alternative. While the minimized indices were not as predictive as the full WQI, they were good for periodic measures. This suggests that some level of river water quality can be monitored with minimal amounts of resources, time and effort.

Alternatively, the condition of the stream may be assessed by assembling collections of insects into an index. Many metrics have been identified and reviewed [46], so inclusion into your study depends on objectives. Most indices use abundance and sensitivity to pollution for water quality determinizations. When using insect indices, the collection method is very important. Available resources for collection, enumeration and taxonomic expertise all impact the metric used. These factors must be established initially to properly assign an index.

The Index of Biotic Integrity (IBI) categorizes the health of a stream using fish populations [47]. Modified versions of the IBI are used to reflect the condition of waters in various regions. Often, multiple metrics are used then summarized to develop an overall metric of water quality. Each metric is scored with a 5 if it reflects a system with very little human influence or a 1 if it departs significantly from a reference stream. A score of 3 is used to describe intermediate qualities. The index is effective yet the criteria for choosing different metrics and selection of reference conditions are issues that need addressed when using an IBI [48]. The index can be strengthened when used in conjunction with other water quality metrics.

Remote sensing, data loggers and modeling are additional methodologies used to quantify water quality. Each method contains limitations, advantages and variable cost so all factors must be weighed before incorporation into an assessment program. The advantages of remote sensing include collection capabilities over very broad areas and documenting comprehensive historical records of change [49]. Collected data can be used to prioritize where to concentrate localized sampling effort but any use must be complimented with ground level measures. It is important to incorporate this type of work with the other methodologies listed. Data loggers such as the HOBO [50] are useful for deployment into rivers to collect sets of continuous data. This is advantageous when monitoring oxygen or conductivity but is limited to these and a few other physical parameters. Water quality models have universal utility to aid decision making and management [51]. Model type, calibration and sensitivity must be carefully selected to ensure the best fit for the study.

4. Protections and management

The regulatory environment surrounding protections of stream ecosystems is vast. All are designed to understand the pollutant loading to the streams, create a plan for minimization and then implement these technologies throughout the built environment. Each addresses different parts of the problem such as point and non-point sources of water pollution.

4.1 Point pollution control

Point source water pollution control occurs throughout the world. In Europe, a directive designed for member states to collect and treat urban wastewater went into effect in 1991 [52]. Freedom was given each state to meet requirements based on reduction goals and receiving water classifications. In the USA, the Environmental Protection Agency (EPA) established the National Pollutant Discharge Elimination Permit (NPDES) program as part of the 1971 Clean Water Act to control any facility discharging waste directly into a stream [53]. In other parts of the world, point source discharge is varied. In China, worsening water quality throughout the major water basins has generated national pollution discharge standards [54]. These standards are technology driven and challenges remain with implementation at the local level. Other parts of the world may be considered even less centrally regulated. While Latin America is known for a system of concentrated central government, water protection law is often spread throughout multiple disparate agencies and ununiformly enforced. Shahady and Boniface [55] reviewed water law in Costa Rica and found five distinct agencies throughout health, sanitation, irrigation, regulation and local water boards with shared responsibility in water protection. This system is very effective in some areas while lacking in others.

This permitting system has shown success toward improving water quality. In the USA, direct reductions in pollutants from wastewater have shown water quality improvements even in large systems such as the Chesapeake Bay [56]. In Europe, clear progress has been made in reducing emissions into urban rivers and lakes; this has been done through connections to sewers, the introduction of wastewater treatment and the upgrading of earlier treatment plants [57]. Elsewhere challenges remain. In much of the developing world urbanization is proceeding at a much faster rate than treatment infrastructure can accommodate [58]. There is room for considerable water quality improvement through point source control in many areas of the world [59].

4.2 Non-point source control

In the USA, the Total Maximum Daily Load (TMDL) program is the current Stormwater Management (SWM) methodology used by the EPA to protect receiving water systems from stormwater pollution. A TMDL calculates the maximum amount of a pollutant that a water body can receive and still meet water quality standards. Once that calculation is made, pollutant allocations (point and non-point) are partitioned throughout all sectors allowing only enough pollutants into the river to maintain identified use. A similar program exists in Europe. River Basin Management Plans (RBMPs) are required documenting impairment from diffuse (non-point) sources and plans for improvement. The idea of pollutant loading identification and then curtailing influx to the river is the consensus for controlling this type of pollution. In fact, some level of SWM is considered an important environmental issue in countries worldwide regardless of their level of development [60].

Successful implementation of SWM requires installation of some type of green infrastructure, changes in land management or permit modifications. Other tools available include mitigation banking [61] and nutrient trading [62]. These tools work in concert with other options to create an economic blueprint to fund the needed reductions to meet SWM requirements.

4.3 BMPs and other protections

For non-point source control, the construction of some type of infrastructure is required due to the diffuse nature of the pollutant. This field has taken on a wide variety of terms [63]. Low Impact Development (LID) is construction that attempts to mimic the natural hydrology and so encompasses any installation that reduces stormwater impact. Water Sensitive Urban Design (WSUD) is a similar approach and includes any effort to minimize the hydrological impacts of urban development on the surrounding environment. Integrated urban water management (IUWM) is a somewhat broader concept combining the management of water supply, groundwater, wastewater and stormwater. Sustainable Urban

Drainage Systems (SUDS) consist of a range of technologies and techniques used to drain stormwater/surface water in a manner that is (arguably) more sustainable than conventional solutions. Best Management Practices (BMPs) are those practices that possess both non-structural (street sweeping) and structural (retention pond) attributes that minimize impact of stormwater. Stormwater Control Measures (SCMs) are identical but this term is used to eliminate the idea of best because alternative practices (not the best ones) can be used. Alternative techniques (ATs) or compensatory techniques (CTs) describe structures used to reduce runoff volume, peak flows and flooding. Some of these techniques can be considered for the protection of the quality of receiving environments. Source Control (SC) is used for on-site stormwater systems. Green Infrastructure (GI) is the part of urban planning that utilizes green space hubs and corridors highlighting their potential ecosystem services.

All technologies are designed to provide benefits to the urban environment and to mitigate the harmful effects of stormwater. The effectiveness of these technologies is dependent on soil characteristics, proper design and installation. Many may be limited by the volume of water flowing into them as retention time is a critical component for effective treatment. Soil is another critical component. A soil with a slow percolation rate cannot handle the volume of water that a good percolating soil is able to infiltrate. The percolation of soil must also be considered in flooding risk. As soil moisture exceeds 45%, pervious areas generate runoff contributing directly to stream discharge. Thus, green infrastructure is now understood to underperform in large and high intensity storm events resulting in flooding [64].

Retention or detention basins and small ponds are the most common technologies installed due to cost and ease of construction. These basins meet multiple design criteria from peak shaving that is required for any land disturbing activity to infiltration by pooling water allowing it to infiltrate. Retention basis (ponds) also provide habitat and recreational opportunities making them appealing in communities. These ponds (<0.01 Km^2) may be responsible for 34% of the nitrogen, 69% of the phosphorus and 12% of the sediment masses retained collectively by all aquatic components in the watershed [65]. More study is needed to quantify the collective impact the network of these small ponds has on urban watersheds.

We now have an ability to create a water sensitive city [66]. This includes the ubiquitous use of plants in any design to create the potential for removal nutrients and other pollutants. Green roofs installed on rooftops now intercept precipitation reliving some of the burden on the stormwater infrastructure and the need for peak attenuation. Building blue roofs to create water storage keeps water out of the stormwater cycle easing the burden on stormwater infrastructure. These alternatives provide a visual improvement over a conventional roof top and a return on investment by lowering environmental costs. They also help to regulate building temperatures improving energy efficiencies. Green design forces water discharge from roads into some form of bioretention further improving water quality [67, 68]. With these designs, stormwater is still flowing but at a reduced rate and with better quality.

Wetlands with or without larger impoundments add water quality treatment, support a diversity of wildlife and provide recreational opportunities within urban environments. The key component of these designs is retention of water in the system. Entering water is spread out evenly and soils constantly inundated to produce the reduced water conditions needed for a wetland. Wetlands can improve stormwater considerably by absorbing flow and mitigating concentrations of nutrients and bacteria [69]. Recreational boardwalks and interpretation signage are additional features these environments provide.

4.4 Stream restoration

In many instances, pollutant source reductions and built SWM infrastructure may not be enough to recapture watershed integrity because of stream channel alteration. In these instances, restoring stream channels is now a preferred goal. In these designs, hydrology, sediment transport and watershed processes that have fundamentally changed are incorporated into a new channel design [70]. In these designs, streambank stabilization, restoration of the stream channel and reestablishment of riparian vegetation are the areas of focus. To stabilize banks, jetties, tree revetments, rock vanes, rock toes, retaining walls and gravel banks are used [71]. While retaining walls and gravel banks provide good stability they are expensive. Jetties may not provide the same level of protection but are the most cost effective measure and provide a more natural look to the restoration. Tradeoffs exist between appearance, effective stabilization and costs.

To rehabilitate the stream channel, regional curve dimensions, planform pattern, and grade control structures are developed [72]. Grade control structures hold the vertical elevation of the stream constant preventing vertical downcutting. Planform pattern creates an alignment of the stream channel to resemble meanders typical for the regional landscape. Proper channel width and depth are created from a "best-fit" consideration using the bankfull channel dimensions of similar reference stream from within the drainage area.

Unfortunately, there is considerable scientific evidence that instream restoration in USA and Europe has shown very limited success [73–77]. Storm events that exceed bankfull have fundamentally changed restoration design reducing expected performance [78]. Restoration of features (stormwater ponds, riparian vegetation) outside the stream channel have shown some improvement but well under expectations based on investment [79]. Prevention remains the single most effective

Figure 2.
Channelized urban river in need of stream restoration.

restoration technique. Lack of effective measure for restoration may be sensitive to time scales as full recovery may take over 15 years to be realized [80].

The how and where to restore is difficult to decide. Urban land is expensive and the best areas may be privately owned and unwelcoming. Projects are driven by available land to municipalities and public sentiments rather than effectiveness in bringing about the best project restoration outcomes [81]. So because of the expense and limited measured effectiveness restoration projects are currently under debate. It appears that good channel restoration projects are best when integrated into multi management efforts including protection of existing good quality stream sections, reducing stormwater flow, controlling sewage overflows upgrading sewage treatment facilities (**Figure 2**) [82].

4.5 Sediment management

Managing sediment in urban stream channels may be paramount for improving urban river systems. Sediment moves through these systems in what can be characterized as the "urban sediment cascade" [83]. In this cascade, sediment is generated from two primary sources; first roads and impervious surfaces and then the bed of the aquatic system. As the sediment flows through this urban cascade it mixes with multiple contaminants such as metals [84] and microplastics [85]. This sediment flows from parts of the urban landscape such as street surfaces, pot holes, storm sewers, ditches and docks eventually entering rivers and lakes. This phenomenon makes every storm event a polluting event with the concentration of contaminates dependent upon the storm intensity.

Once in the stream bed this sediment may accumulate for extended periods of time. Evidence suggests movement of sediment fractions larger than the median size of the bed surface material is rare and occurs only at relatively high flows [86]. Such flows may occur once every few years and the movement might not last more than a few hours. This further suggests years of accumulation of contaminated sediment may be severe and pose a possible health risk [87]. Removal of dams as part of an overall restoration strategy to improve fish passage and sediment flow downstream may in actuality be counterproductive toward restoration goals as beneficial evidence of this practice is highly experimental [88, 89]. Prevention or clean up through practices such as street sweeping may be a better management strategy [90].

4.6 Citizen science and education

The importance of citizen science protecting water quality [91] is becoming more widespread and may be integral to restoring these systems. It bridges the gap between regulators and the public energizing citizens living in urban areas impacted by poor river quality. Citizens can be trained to complete essential tasks, are affordable and can generate good data when verified [92]. Programs such as the The Izaak Walton League's Save Our Streams [93] builds an army of volunteers through training and information to monitor our waterways. This program serves as an intermediary successfully uncovering problems and urging local leaders to take action. These types of programs can even transcend data collection and scientific analysis moving those involved toward a greater sense of place in the watershed [94]. This can further the idea of watershed protection and lead to real policy change.

Education is the other effort underway to secure river protection. Theoretically, an educated public will hold regulators and developers responsible for their actions. Programs such as Global Rivers Environmental Education Network (GREEN) educates global citizens about water quality problems [95]. Education based curriculum teaching stormwater principles in schools educates future generations about the problems rivers are facing [96]. Such programs are productive. But education is complex. People formulate perceptions about the environment using various levels of experience, normative influences, temporal discrepancies and attitude-behavior measures [97]. Why should people care or why be involved? Answers to these questions are extremely diverse, complex, and poorly understood. The furtherance of educational understanding can only enhance opportunities for improvement.

5. Conclusions

There is general agreement that urban water resources need to be managed better. We all depend on clean water for survival and the make-up of our communities reflects the quality of water resources flowing through them. The need for improvement is great and good policy needs both the natural and social sciences to generate good governance of our water resources [98]. But urban water management seems stuck in a state of maladaptation essentially locked into a societal need for large infrastructure and the never ending need to maintain it [99]. Change only occurs in response to some catastrophic or shock event (such as a flood) that in no way bears the needed one-on-one logical change to what triggered the shock event in the first place. This leads to changes in urban infrastructure that may bear no resemblance to real societal needs or watershed management.

What is ultimately needed is water policy adapted to societal needs instead of knee jerk responses to a crisis. Resources spent on stream restoration and flood mitigation upstream will be well received when urban residents understand the benefits downstream [100]. Local efforts to pick up trash and minimize plastics may have far reaching impact on communities when understood in the context of the world's oceans [101]. Or the necessity to rebuild current infrastructure to deal with ongoing climate driven precipitation change [102]. Good monitoring can expose the need and document the improvement. Urban rivers can be rehabilitated given a dedicated citizenry aided by governmental and scientific support. Our future depends on it.

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